

Peak-Seeking Optimization of Trim for Reduced Fuel Consumption

Flight-Test Results

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Outline

Background

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- Research Control Law

- Peak-Seeking Algorithm

- Flight-Test Technique

- Flight-Test Results

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 - Varying Flight Condition

 - Performance Metrics

- Conclusions

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- Backup





Introduction

- ▶ US domestic flights in 2011:
 - ▶ 12.1 billion gallons of fuel
 - ▶ 114.6 million metric tons of CO₂ equivalent
- ▶ NASA Environmentally Responsible Aviation project
 - ▶ Mitigate impacts of aviation on the environment
 - ▶ Reduce fuel consumption and emissions



State-of-the-art

- ▶ Airplanes use scheduled trim solutions
- ▶ Trim designed a priori with
 - ▶ Models
 - ▶ Wind-tunnels
 - ▶ Flight-test data
- ▶ Scheduled trim solutions may not address:
 - ▶ Operating in off-nominal flight conditions
 - ▶ Subtle manufacturing differences compared to aircraft of the same type
 - ▶ Modifications such as winglets, external stores, blisters, engine upgrades, or repairs to damage
 - ▶ Increased flexibility with age, leading to a different wing shape under load



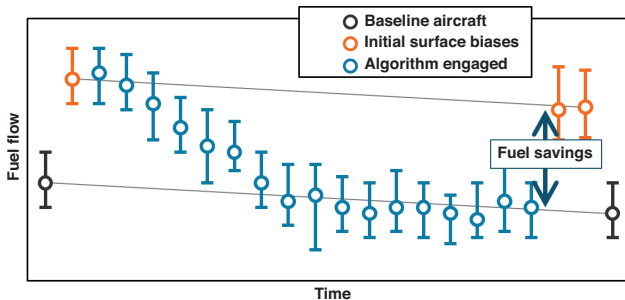
Real-time trim optimization

Concept

Use real-time performance measurements to tune trim setting

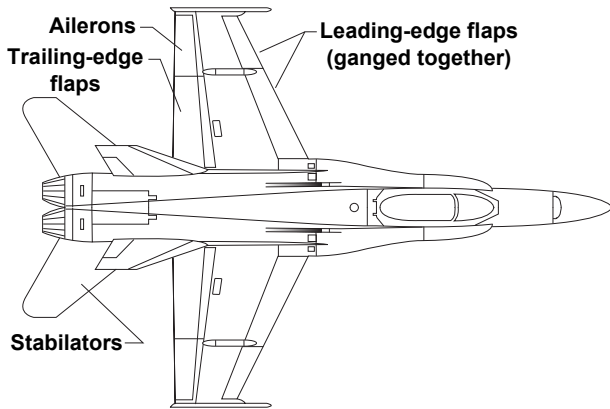
- ▶ Small but meaningful fuel savings possible
- ▶ Noisy measurements are challenging
- ▶ Multiple effectors

Notional test point



Modified F/A-18, tail number 853

- ▶ Primarily a flight controls research platform
- ▶ Heavily instrumented, including fuel flow meters
 - ▶ Production fuel flow meters
 - ▶ Research-grade fuel flow meters
- ▶ Experiment software has full authority over surfaces & throttles
- ▶ Reverts to production control system if a constraint is violated





Research control law

- ▶ Inner loop: Non-linear dynamic inversion (Miller)
- ▶ Research autopilots
 - ▶ Altitude hold
 - ▶ Airspeed hold
 - ▶ Wing leveler

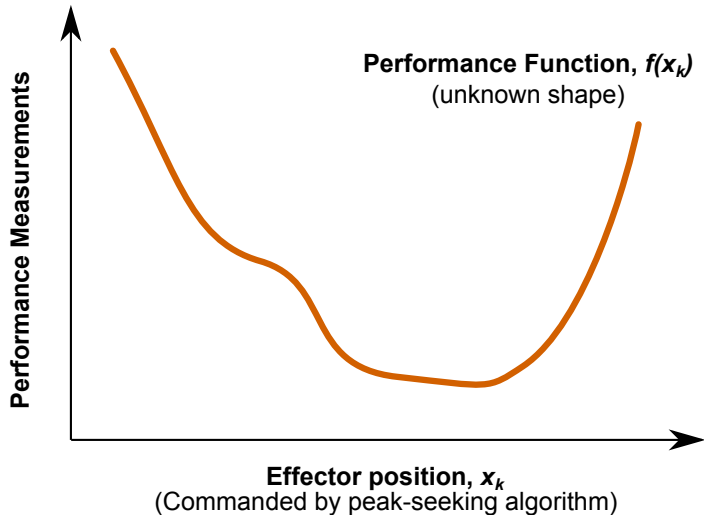


Peak-seeking algorithm, simplified example



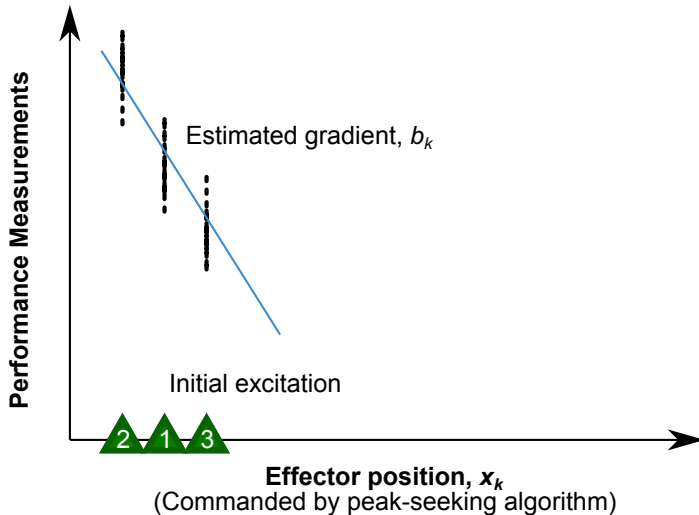


Peak-seeking algorithm, simplified example



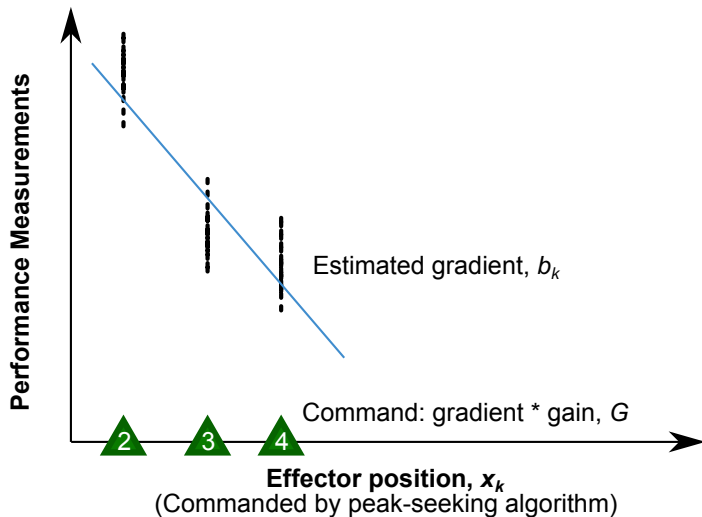


Peak-seeking algorithm, simplified example



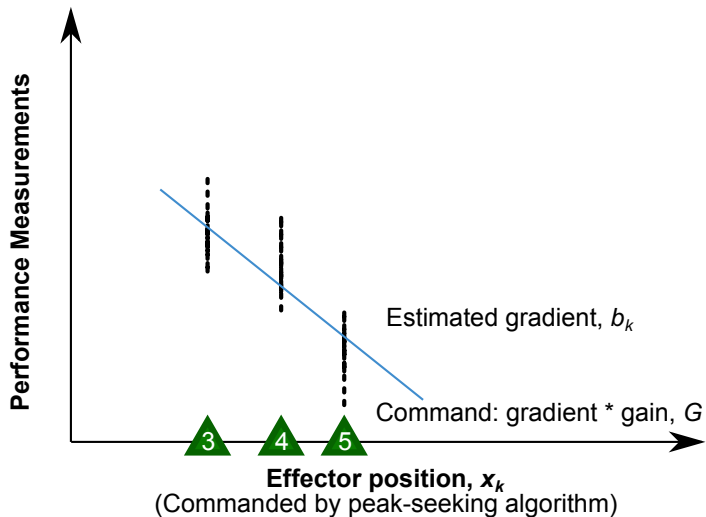


Peak-seeking algorithm, simplified example



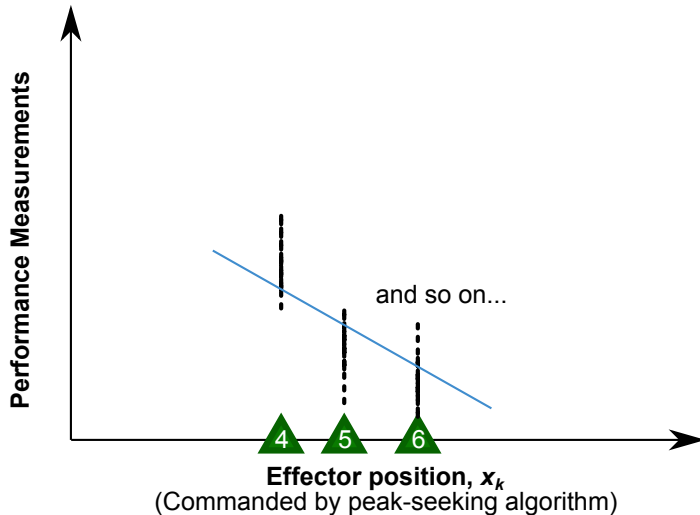


Peak-seeking algorithm, simplified example

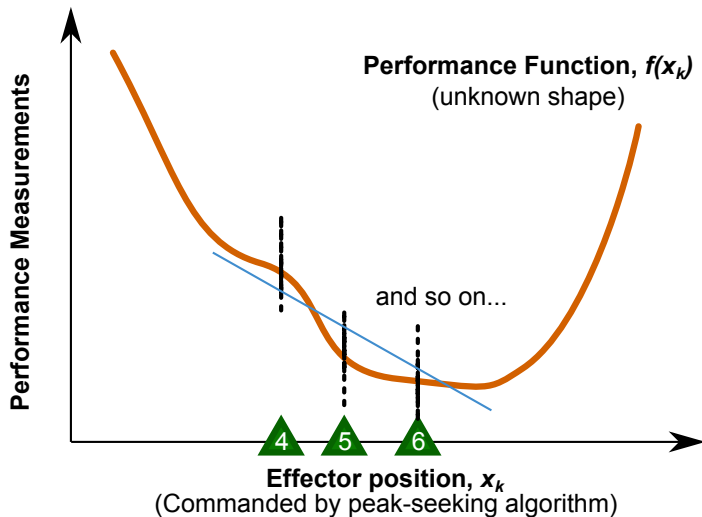




Peak-seeking algorithm, simplified example

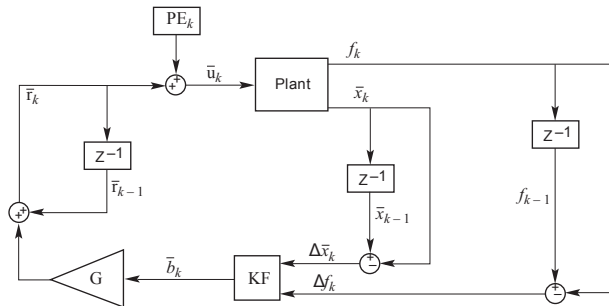


Peak-seeking algorithm, simplified example



Peak-seeking algorithm architecture

Peak-seeking algorithm architecture

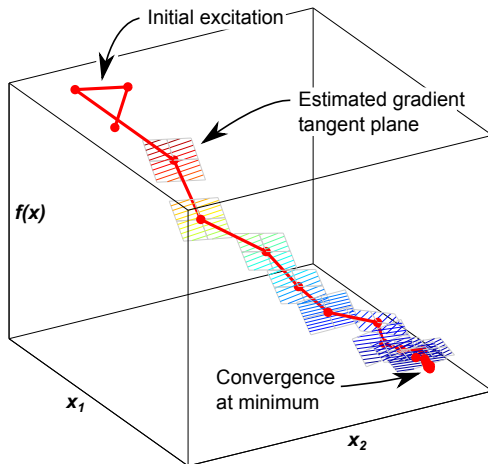


KF Time-varying Kalman filter

PE Persistent excitation

Plant Aircraft, NDI, & autopilot

Notional 2-effector example





Design parameter variations

G Gain applied to estimated gradient

M Number of measurements for gradient estimate (3, 5, 7, & 10)

N Number of independent effector groups controlled by algorithm

f Performance measurement signal

- ▶ Research fuel flow meters
- ▶ Power lever angle (throttle position)
- ▶ Production fuel flow meters

Window Width of time-averaging window in seconds (10, 20, & 40)



Test parameter variations

IC Initial configuration

- ▶ Production trim configuration (baseline)
- ▶ High-drag “corner” alternative trim configurations

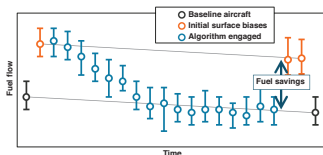
▶ Initial trim sets

KCAS Knots calibrated airspeed

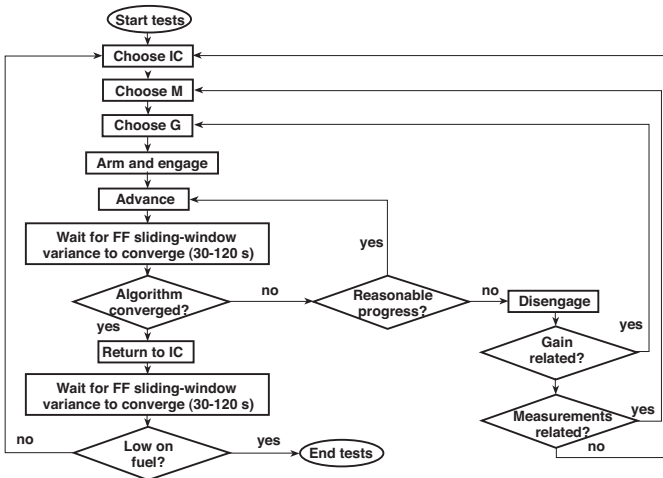
- ▶ 240 kn
- ▶ 200 kn



Flight-test technique



- ▶ Manual advance of algorithm iterations
- ▶ Control room “audibles” for pilot-selected mode
- ▶ Approximately 20 min per test point





Selected test results

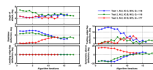
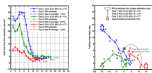
► Test configurations flown

Comparison

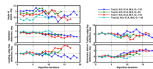
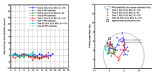
Convergence

Surface positions

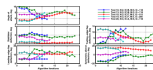
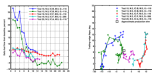
Nominal results



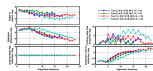
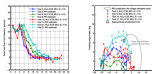
Initial configuration A



Varying flight condition

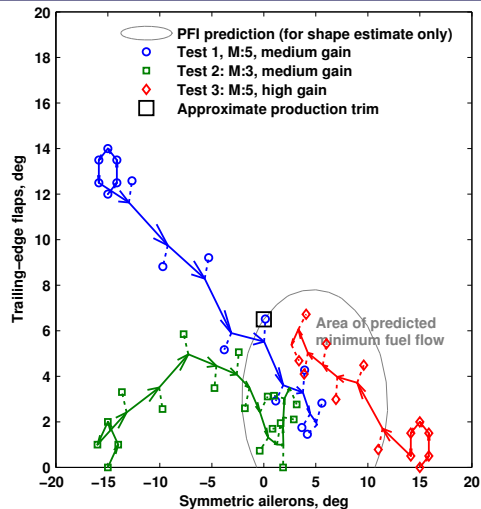
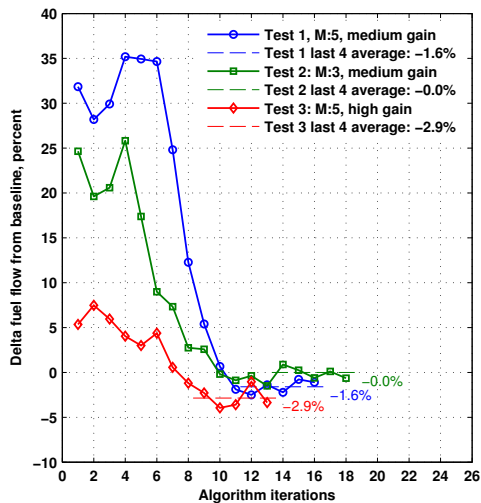


Performance metrics



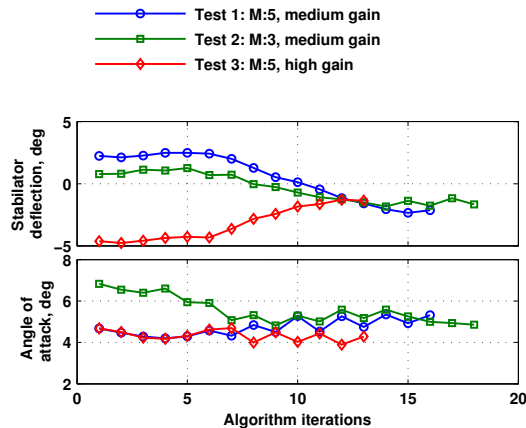
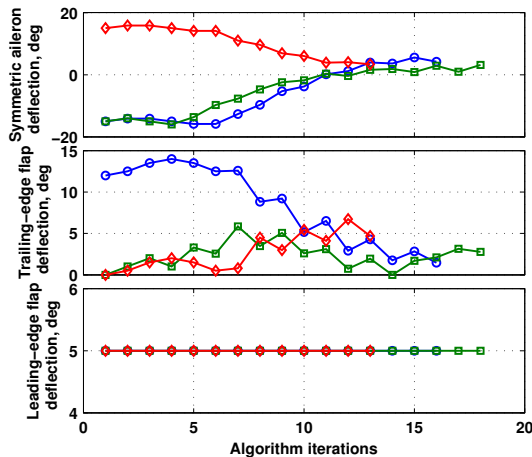


Algorithm convergence - first three tests



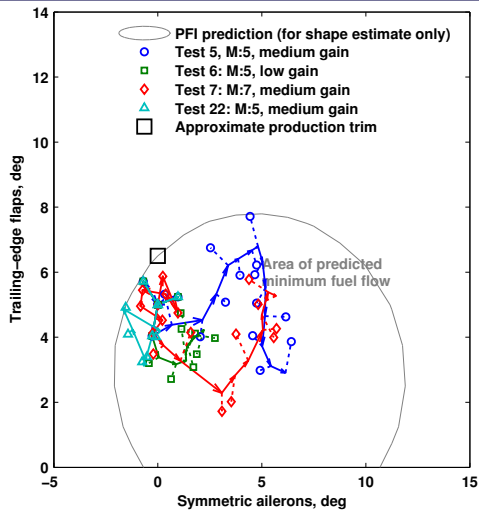
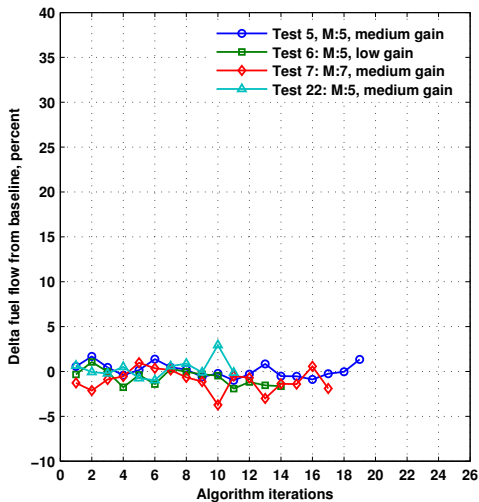


Surface positions - first three tests



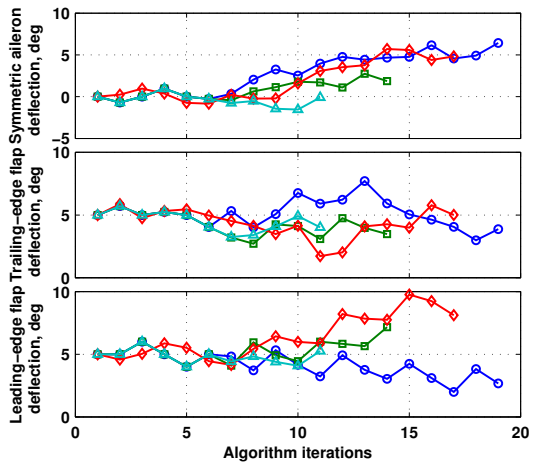


Algorithm convergence - initial configuration set A

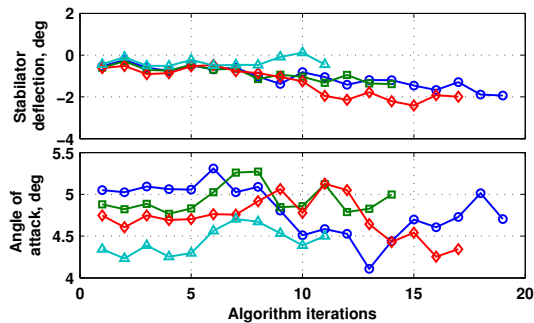




Surface positions - initial configuration set A

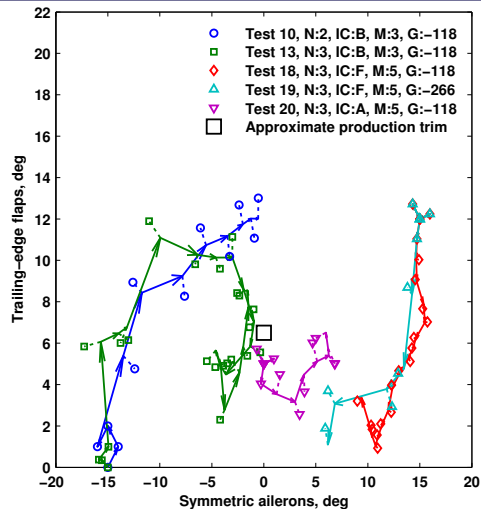
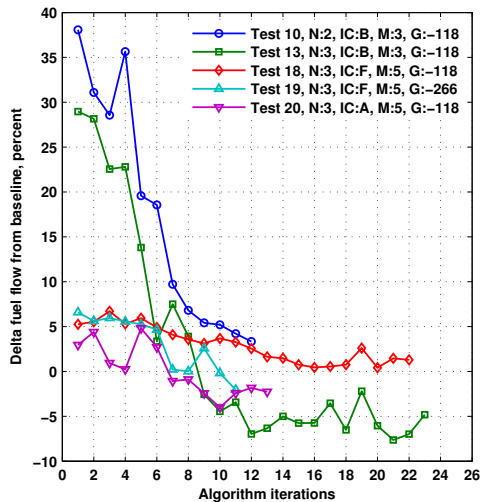


- Test 5: M:5, medium gain
- Test 6: M:5, low gain
- Test 7: M:7, medium gain
- Test 22: M:5, medium gain



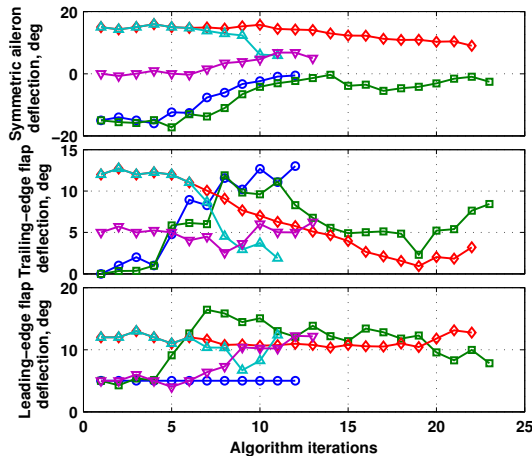


Algorithm convergence at 200 KCAS flight condition

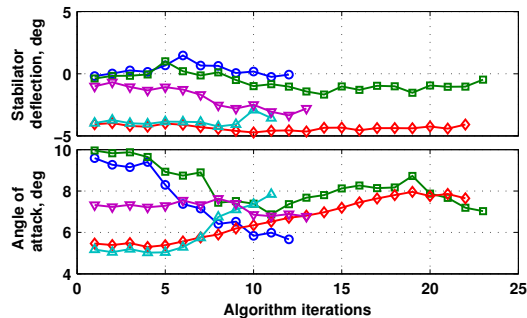




Surface positions at 200 KCAS flight condition

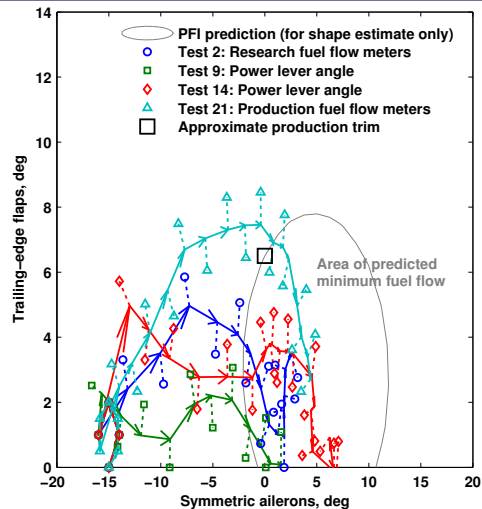
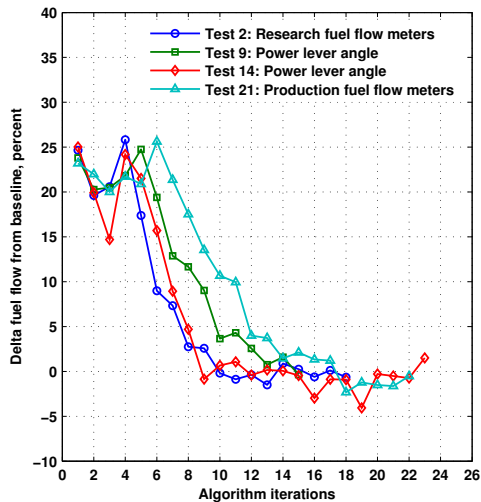


- Test 10, N:2, IC:B, M:3, G:-118
- Test 13, N:3, IC:B, M:3, G:-118
- Test 18, N:3, IC:F, M:5, G:-118
- Test 19, N:3, IC:F, M:5, G:-266
- Test 20, N:3, IC:A, M:5, G:-118



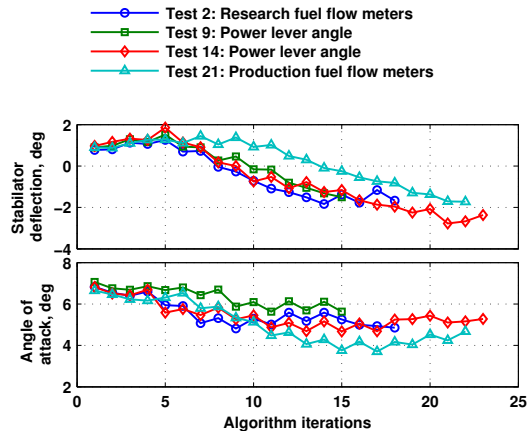
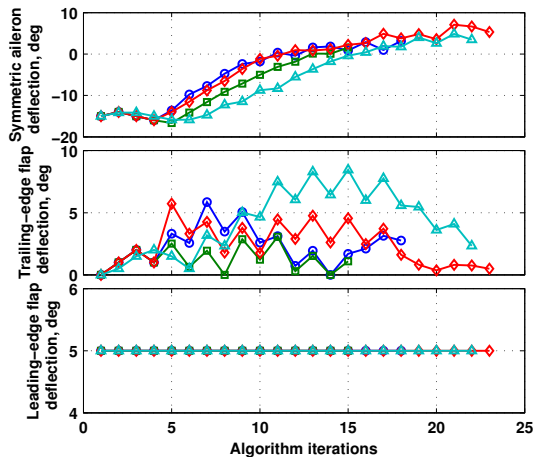


Algorithm convergence with various performance metrics





Surface positions with various performance metrics





Conclusions

Six research flights

- ▶ Algorithm consistently converged on low fuel flow trim configurations
- ▶ Trim setting found requiring approximately 3% less fuel flow vs baseline
- ▶ Fuel savings of 1% to 2% were more typical
- ▶ Research-grade fuel flow meters were not required
- ▶ Algorithm performed well at two flight conditions
- ▶ Pilots noted that algorithm did not impact ride quality



Future research

- ▶ Transport-class aircraft
- ▶ Aircraft with external stores
- ▶ Lateral-directional axes
- ▶ Supersonic regime, longitudinal lift distribution, wave drag
- ▶ Test algorithm in moderate turbulence
- ▶ Generate guidelines for implementation on other aircraft
- ▶ Increased automation
 - ▶ Advancement of algorithm
 - ▶ Disengage for maneuvering
 - ▶ Suspend iterations for turbulence



Questions/contact

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Test configurations flown

















◀ Selected results

Test	Flight	KCAS	Performance function, f	IC set	N	Window, s	M	G
1	1	240	Research FF	C	2	20	5	-118
2	1	240	Research FF	B	2	20	3	-118
3	1	240	Research FF	D	2	20	5	-177
4	1	240	Research FF	F	3	20	5	-118
5	2	240	Research FF	A	3	20	5	-118
6	2	240	Research FF	A	3	20	5	-53
7	2	240	Research FF	A	3	20	7	-118
8	2	240	Research FF	E	3	20	5	-118
9	3	240	Power lever angle	B	2	20	3	-118
10	3	200	Research FF	B	2	20	3	-118
11	3	240	Research FF	A	3	10	10	-59
12	3	240	Research FF	A	3	40	3	-118
13	4	200	Research FF	B	3	20	3	-118
14	4	240	Power lever angle	B	2	20	3	-118
15	4	240	Research FF	A	3	10	10	-133
16	4	240	Research FF	A	3	20	10	-133
17	4	240	Research FF	A	3	40	3	-118
18	5	200	Research FF	F	3	40	5	-118
19	5	200	Research FF	F	3	40	5	-266
20	5	200	Research FF	A	3	20	5	-118
21	5	240	Production FF	B	2	40	5	-118
22	5	240	Research FF	A	3	40	5	-118



Selected test results

► Test configurations flown

Comparison	Test numbers	Convergence	Surface positions
Nominal results	1, 2, & 3	 	 
Initial configuration A	5, 6, 7, & 22	 	 
Varying flight condition	10, 13, 18, 19, & 20	 	 
Performance metrics	2, 9, 14, & 21	 	 



Flight conditions and initial trim sets

Flight conditions

- ▶ 25k ft MSL, 240 KCAS
- ▶ 25k ft MSL, 200 KCAS

Initial effector biases in degrees

Set	Ailerons	TEF	LEF
A	0	5	5
B	-15	0	5
C	-15	12	5
D	15	0	5
E	15	12	0
F	15	12	12

TEF Trailing-edge flaps

LEF Leading-edge flaps



Previous research: Real-time trim optimization

- ▶ Performance Seeking Control, F-15 (Orme et al.)
 - ▶ Stabilators
 - ▶ Variable cowlings
 - ▶ Inlet ramps
 - ▶ Nozzles
- ▶ Adaptive Performance Optimization, L-1011 (Gilyard et al.)
 - ▶ Symmetric ailerons
 - ▶ Model to estimate drag
 - ▶ Drag reduced by approximately 1%
- ▶ Extremum-seeking control, simulation studies (Krieger and Krstic)
 - ▶ Optimizing airspeed for best endurance
 - ▶ Atmospheric turbulence as only excitation



Previous research: Peak-seeking control

- ▶ Formation flight for fuel savings
 - ▶ Position in formation (Binetti et al.)
 - ▶ Position in formation (Ryan and Speyer)
 - ▶ Spanwise lift distribution (Hanson and Ryan)
- ▶ Trim optimization
 - ▶ Single effector group: X-48B simulation studies (Griffin et al.)
 - ▶ Three effector groups: F/A-18 simulation studies (Schaefer and Brown)¹

¹Companion paper